Chapter 8

Debris Flows in Grand Canyon and the Rapids of the Colorado River

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Introduction

Coarse sediment—gravel, cobbles, and boulders—is transported to the Colorado River almost exclusively by debris flows, which are irregularly occurring types of flash flood events. By supplying boulders that exceed the capacity of the river to move them at most discharges, debris flows create and maintain the hundreds of debris fans and associated rapids that control the lengthwise or longitudinal profile of the Colorado River in Grand Canyon. Debris flows occur in 740 tributaries of the Colorado River in Grand Canyon between Lees Ferry (at RM 0) and the Grand Wash Cliffs (at RM 277), the physical feature that marks the western boundary of Grand Canyon National Park and the end of Grand Canyon.

Coarse sediment is of interest within the Glen Canyon Dam Adaptive Management Program because of its relation to key components of the Colorado River ecosystem. The deposition of coarse-grained sediment at tributary junctures builds large debris fans that constrict the river and form rapids. Debris fans and debris bars, which develop below rapids, create the fan-eddy complex that is the cornerstone of the physical framework of the river in Grand Canyon (fig. 1). In addition, the pools upstream and downstream of debris fans slow sediment movement or trap it for temporary storage. The pool-drop system created by debris fans is prime habitat for the endangered humpback chub (*Gila cypha*), while coarse sediment injected into the river during debris flows is used by other aquatic organisms, notably the alga *Cladophora glomerata*. The navigation of the river by whitewater boaters also can be affected by debris-flow events.

Monitoring the input of coarse sediment into the Colorado River ecosystem and its long-term redistribution by the river is critical to understanding how dam operations affect coarse sediment deposition and, indirectly, other ecosystem components. Scientists are able to model debris-flow magnitude and frequency from extensive data sets developed through long-term monitoring. Also, this chapter estimates the amount of sediment contributed by debris flows and models its deposition at tributary junctures to evaluate the effects of debris flows over several temporal and spatial scales, including the recent period of operations of Glen Canyon Dam. Data are combined with modeling to evaluate long-term changes in rapids and to explain large-scale features. The chapter also summarizes data from debris-fan monitoring activities by the U.S. Geological Survey's

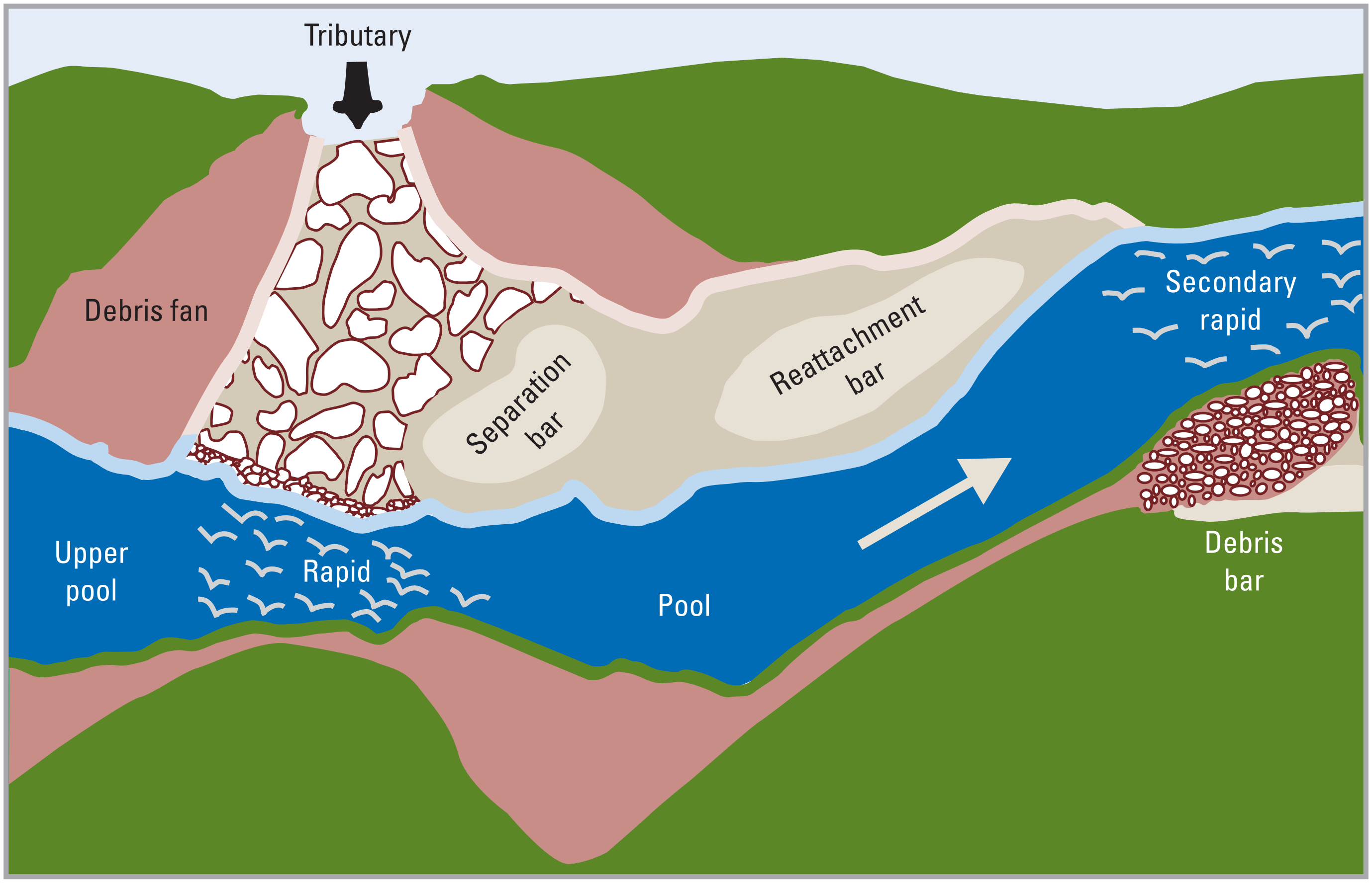

Figure 1. Diagram showing a fan-eddy complex in Grand Canyon. Debris flows from tributary canyons carry coarse sediment that is deposited at the juncture with the Colorado River, forming deposits called debris fans. Debris fans constrict the Colorado River and raise its bed elevation, creating rapids. Especially during floods, the river entrains the sediment on the debris fan and transports it downstream through the pool, where the larger particles become lodged on debris bars that form secondary rapids. Between the constrictions of the primary and secondary rapids, pools and eddies form, creating a depositional setting for sandbars.

(USGS) Grand Canyon Monitoring and Research Center (GCMRC) and research by Water Resources and Geology Discipline scientists. Finally, the chapter considers the role of experimental high flows and the modified low fluctuating flow (MLFF) alternative on coarse-sediment reworking.

Background

Distributed along 277 mi (446 km) of river between the Paria River and Grand Wash Cliffs, the 740 tributaries that produce debris flows drain 4,600 mi^2 (12,000 km^2) of steep terrain between the north and south rims of Grand Canyon (Webb and others, 2000). Debris flows, which are typically more than 80% sediment by weight, are slurries of clay to boulder-sized sediment mobilized during periods of intense or sustained precipitation. The exposed bedrock landscape of Grand Canyon National Park provides an ideal setting for the initiation of debris flows: high relief combines with differential rock strength to create a high potential for slope failure (Griffiths and others, 2004). Most slope failures that become debris flows (75%) occur in the Hermit Formation and Esplanade Sandstone of the Supai Group and in the Muav Limestone and Bright Angel Shale of the Tonto Group (fig. 2a). Other prominent sources include the Dox Sandstone, Cardenas Lava, Vishnu Schist, and Quaternary Basalts in western Grand Canyon. Tributaries are documented to have produced debris flows throughout the Holocene (Melis and others, 1994; Hereford and others, 1998).

In Grand Canyon, debris flows are initiated by a combination of intense precipitation and subsequent slope failure (Cooley and others, 1977; Webb and others, 1988, 1989, 1999b, 2000, 2004; Griffiths and others, 2004). The most common type of slope failure is termed the "firehose effect" (Melis and others, 1994) (fig. 2b), where streamflow falling over cliffs, typically in the Redwall Limestone, strikes bedrock and accumulated colluvium and causes slope failure and mixes these materials and water to form a slurry. Debris flows that reach the Colorado River deposit their material on debris fans. These enlarged or aggraded debris fans constrict the river and raise the riverbed elevation until mainstem flows rework coarse-grained deposits (Webb and others, 1989). "Reworking" is a term describing river entrainment and transport of particles from debris fans, including the winnowing of fine-grained particles (clay to cobble size) and the movement of boulders, either on the fan surface or into the river. The large boulders that remain after this reworking form the core of rapids that modify the longitudinal profile of the river and locally control the physical framework of the present-day Colorado River in Grand Canyon (Webb, 1996).

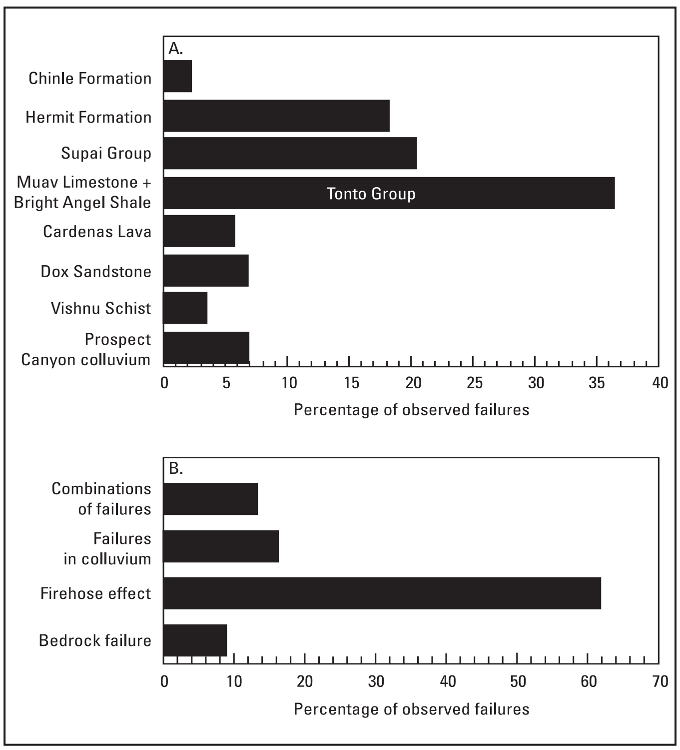

Figure 2. A. Relative frequency of the location at which slope failures in bedrock or colluvium resulting in debris flows that reach the river (n = 101, 1939 through 2003) have occurred in Grand Canyon. B. Relative frequency of initiation mechanisms for selected debris flows from 1939 through 2003 in Grand Canyon (n = 68) (from Griffiths and others, 2004).

Debris-fan reworking was extensive before construction of Glen Canyon Dam. Reduced peak flow on the regulated river represents a fourfold decrease in its sediment-transport potential compared to predam conditions (Howard and Dolan, 1981). As a result, ability of the river to erode newly deposited sediment from debris fans has been reduced. Reworking still occurs on a limited basis, typically during maximum powerplant releases or intentional flood releases from Glen Canyon Dam (Webb and others, 1999a). Today, because the reworking by the Colorado River is limited, debris flows from unregulated tributaries are now an effective agent of change in the river corridor (Howard and Dolan, 1981), affecting the water-surface profile, hydraulics through rapids, and the associated pools and eddies downstream.

Status and Trends

Debris-flow Frequency

Debris flows in Grand Canyon were relatively well documented in the 20th century (Webb, 1996; Webb and others, 2000; Griffiths and others, 2004). We use the term Grand Canyon loosely to collectively refer to the river corridor from Lees Ferry to the Grand Wash Cliffs, merging Marble and Grand Canyons and their respective subreaches. Direct observations provided a complete record of debris flows from 1984 to 2004 (fig. 3), which was augmented with repeat photography, such as that shown in figure 4, that provides a separate record (1890 through 1983) of debris flows from 147 tributaries. In this analysis, we only documented debris flows that reached debris fans and/or the Colorado River; we did not include debris flows that occurred upstream in tributaries but did not reach the river corridor.

Direct Observations (1984–2004)

Debris flows, rockfalls, and significant streamflow floods were directly observed or compiled from the accounts of river runners along the river in Grand Canyon from 1984 through 2004. These data provide a complete record of debris flows that reached the Colorado River from all Grand Canyon tributaries for more than 21 yr (fig. 3). During this period, a total of 104 events occurred in 88 tributaries for an average of 4.95 debris flows per year. A total of 14 debris flows occurred in 2001 and again in 2002, the most prolific period in the record. Webb and others (2000) analyzed

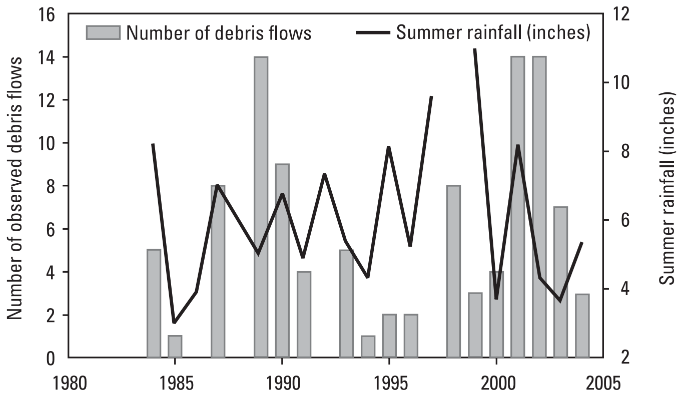

Figure 3. Observational record of debris flows in Grand Canyon, from 1984 to 2004, compared with total summer rainfall (July through September) at Grand Canyon National Park airport. No data are available for summer precipitation in 1997.

precipitation records around Grand Canyon and found that the annual number of debris flows is not related to total summer precipitation (as illustrated by the precipitation record shown in fig. 3 in conjunction with annual debris flows). This suggests that antecedent moisture has little effect on debris-flow occurrence (Griffiths and others, 2004).

Most debris flows occurred in Marble Canyon or eastern Grand Canyon, with notable exceptions at Lava Falls Rapid (RM 179) in 1995 (Webb and others, 1999b) and between RM 189 and RM 209 from 1999 through 2001. Several tributaries delivered more than one debris flow to the river between 1984 and 2004. For example, Seventyfive Mile Creek had four debris flows, and Monument Creek (RM 93.9) had three. Multiple debris flows within a drainage basin suggest that slope and channel destabilization caused by the initial event may lead to repeated events until either the loosened sediment is removed or sufficient time elapses between severe storms to allow healing of hillslopes and channel margins.

Repeat Photography and Debris Flows (1890–1983)

Repeat photography (fig. 4) has been used in numerous studies in Grand Canyon to document long-term changes in both terrestrial ecology and geomorphology (Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb and others, 1989, 1999a; Melis and others, 1994; Webb, 1996; Griffiths and others, 2004). This type of scientific photography is particularly useful for

A.

B.

Figure 4. Repeat photographs of Crystal Rapid. A. (February 9, 1890) This downstream view from the right scout point at Crystal Rapid (RM 98) shows a wide, gentle rapid during the second expedition through Grand Canyon. This expedition, led by Robert Brewster Stanton, occurred in winter 1890. The deepest water in the rapid is on river right, and emergent rocks are on the left side (R.B. Stanton, courtesy of the National Archives and Records Administration, College Park, Maryland). B. (February 1, 1990) A debris flow in 1966 constricted the river by more than 80%, creating what was considered the most formidable rapid in Grand Canyon. Floods between 1966 and 1986 widened out the constriction, reducing the navigational hazard this rapid posed. Although Crystal Rapid has lost some of its ferocious reputation, it remains one of the largest in Grand Canyon (T. Brownold, stake 1471).

evaluating the types of landscape changes associated with debris flows. Most of the information for historical debris flows was obtained through comparison of repeat photography and historical photographs taken between 1871 and 1964. Between 1989 and 2002, 1,365 historical photographs of the river corridor were matched to determine significant changes to tributary channels, debris fans, and rapids throughout the canyon. The year with the most abundant and widespread coverage is 1890, when the well-documented Stanton expedition occurred (Webb, 1996). Several sets of low-altitude aerial photographs taken between 1935 and 1984 were also analyzed for evidence of debris flows at the river.

To determine the frequency of debris flows at the river from 1890 through 1983, the 1890 photographs and their matches were interpreted for evidence of debris-flow occurrences at 147 debris fans. This process revealed that debris flows occurred at 84 of 147 tributaries (Griffiths and others, 2004), indicating that 57% of the tributaries generated one or more events from 1890 through 1983. Because any of these 84 tributaries could have delivered more than one debris flow, additional data, such as written accounts, were used to identify a total of 93 debris flows from the 84 tributaries over a period of a century. From 1890 through 1983, 6% of tributaries produced two or more debris flows, including five at Lava Falls Rapid (RM 179) (Webb and others, 1999b).

Analysis of aerial photograpy identified an additional 23 debris flows for a total of 107 debris flows that occurred between 1890 and 1983 at the mouths of 167 tributaries from Glen Canyon Dam to Separation Rapid (RM 240), the head of Lake Mead. Using this data set as an unbiased sample of the entire population of 740 tributaries, the rate of debris-flow occurrence at the river is estimated at 5.0/yr for all tributaries from 1890 through 1983. This rate is essentially identical to the 4.95/yr frequency observed between 1984 and 2004. If the results for both records are combined, 211 debris flows are known to have occurred along the Colorado River in Grand Canyon between 1984 and 2003.

Net Observed Effects of Debris Flows

Of the documented 211 historical debris flows in 172 tributaries, 55 significantly affected the Colorado River by creating rapids or increasing constrictions during the past century (Webb, 1996; Webb and others, 2000; Griffiths and others, 2004). From 1984 through 2004, 8 rapids were created, and 15 were constricted by debris flows. The observational evidence indicates that the occurrence of debris flows is not spatially random in Grand Canyon. Debris flow activity is particularly concentrated in Marble Canyon and other reaches where the river trends towards the southwest or south-southwest. The findings indicate that about 10% of tributaries had two or more debris flows in the last century, with a maximum of six debris flows at Lava Falls Rapid (Webb and others, 1999b) and five debris flows at Seventyfive Mile Creek during the 20th century.

Modeling Debris-flow Frequency

Griffiths and others (1996) developed a model of debris-flow frequency (1890–1990) in Grand Canyon between Lees Ferry and Diamond Creek (RM 0 to RM 226), and Webb and others (2000) extended that model to the Grand Wash Cliffs (RM 277). The model identified several parameters that are significantly related to the occurrence of debris flows that reach the river, including the presence and location of shale in the basin, drainage-basin area, mean drainage-basin gradient, and the aspect of the river corridor. Drainage-basin variables that are the most significant in influencing the occurrence of debris flows are suggested in a map showing the distribution of debris-flow probabilities (fig. 5). One tendency is for debris-flow frequency to decrease when the river corridor trends away from a southwesterly course; Griffiths and others (2004) attributed this to the regional trajectory of summer storms, which tend to move from the southwest. The effect of drainage-basin area is evident in Marble Canyon, where the largest tributaries have a higher probability of debris-flow occurrence. The height of the Hermit Formation and the gradient from this unit to the Colorado River appear to be especially important in Marble Canyon and reflect the dominant contribution of shale units to debris flows in Grand Canyon.

In eastern Grand Canyon, a greater variety of source materials, combined with structural variability, resulted in a mosaic of probabilities (fig. 5). The presence of and gradient below shales strongly affect debris-flow probability. River aspect and drainage-basin area are significant but less influential in this reach. Certain sections of the river corridor that trend northwesterly generally have tributaries with low probabilities. In western Grand Canyon, the presence of three source formations and the overall gradient of each tributary from headwaters to river strongly influenced debris-flow probability. The height of the Hermit Formation is less influential in western than eastern Grand Canyon or Marble Canyon

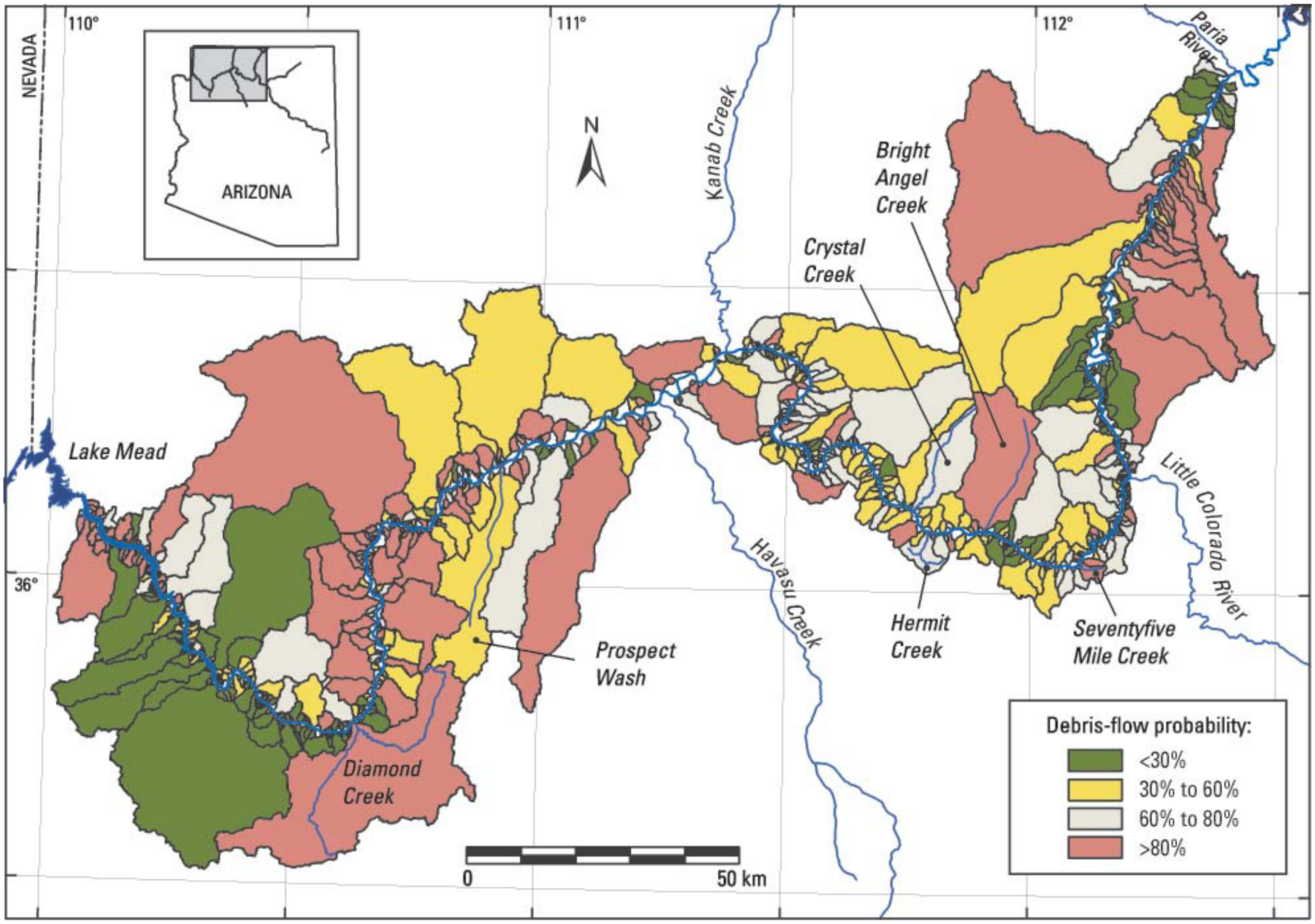

Figure 5. Debris-flow probabilities of 740 tributaries of the Colorado River in Grand Canyon (Griffiths and others, 2004). This map depicts group probabilities of the occurrence of one or more debris flows in a tributary during the century between 1890 and 1990.

because that formation is farther from the river. Debris-flow probability is lowest downstream from Diamond Creek, where the river trends northwesterly, except in the reach immediately upstream from the Grand Wash Cliffs, where debris-flow probabilities are high because of the proximity of shales to the river corridor.

Our observations and statistical analyses show that (1) all 740 Grand Canyon tributaries produce debris flows, albeit some at a low frequency; (2) about 60% of tributaries produce one or more debris flows per century; (3) about 10% of tributaries produce two or more debris flows per century; and (4) no tributary has produced more than six debris flows in the last century.

Debris-flow Sediment Yield

Data on debris-flow frequency, volume, and particle-size distributions were combined to create a model of debris-flow sediment yield in Grand Canyon (Webb and others, 2000). Using this model, it is estimated that debris flows contribute between 155,000 and 325,000 tons/yr (141,000 and 295,000 Mg/yr) of sediment to debris fans in Grand Canyon. Marble Canyon contributes the greatest amount of debris-flow sediment, which is consistent with both empirical observations and the modeled distribution of debris-flow occurrence in Grand Canyon (Griffiths and others, 2004).

Modeling debris-flow sediment yield requires a number of important assumptions. In this case, it was assumed that all debris flows from a given tributary were the same size, which means the model does not realistically depict a magnitude-frequency relation. Furthermore, the sediment-yield model does not account for extreme events not included in the historical record and small events that are inadequately represented. Some of these problems could be resolved by using a fully stochastic model of debris-flow frequency, but objectively determining model constraints based on the limited data would be difficult.

Incorporating an average boulder content of 14% of debris-flow volumes (Melis and others, 1994; Webb and others, 1999b, 2000), the total boulder delivery from all 740 tributaries is 1.1 billion ft^3 (31 million m^3) per thousand years. Distributing these boulders evenly along the river corridor without removal, dissolution, or erosion raises the bed by 2.4 ft (0.7 m) per thousand years, which we consider to be a reasonable order of magnitude. To distribute boulders more realistically, deposition was limited to the areas of recent debris fans, calculating the area of deposition at each tributary confluence as a rectangle defined by the length and average width of the rapid. For each confluence, local bed rise was calculated by dividing the total volume of sediment delivered by debris flow by the estimated area of deposition; these results were reported in Webb and others (2000, 2004).

River Reworking of Aggraded Debris Fans

In the years immediately following a debris flow, Grand Canyon rapids are known to be unstable because of reworking by the Colorado River (Howard and Dolan, 1981; Kieffer, 1985; Webb and others, 1989, 1999b; Melis and others, 1994). Before closure of Glen Canyon Dam in 1963, the Colorado River removed most debris-flow deposits during the early summer floods, which averaged 82,000 cubic feet per second (cfs) and were as large as 220,000 cfs. Those flood events swept all but the largest particles downstream and redeposited cobbles and small boulders on debris bars that constrained the extent of eddies and controlled secondary rapids. The interaction between the frequency and magnitude of tributary debris flows and mainstem floods resulted in debris fans and rapids that were relatively stable in the intervening time periods between debris flows.

Lava Falls Rapid offers one of the best documented cases of debris-fan reworking, which occurred during the 1996 beach/habitat-building flow (fig. 6) and during other floods in the predam and postdam periods (Webb and others, 1999b). Most of the reworking that occurred during the 1996 event happened as the discharge increased to its peak; reworking slowed markedly during the first day of peak discharge. Nine radio-tagged boulders traveled an average distance of 262 yards (240 m) from their initial positions on the Prospect Canyon debris fan during the 1996 event (Pizzuto and others, 1999; Webb and others, 1999b). Debris-flow deposits in 1939, 1954, 1955, 1963, and 1966 were also reworked by subsequent floods; some of the aggraded debris fans (1954, 1963, 1966) were completely removed, while some of the deposition (1939, 1955) remained to cause persistent changes in Lava Falls Rapid.

While Kieffer (1985) stated that exceptionally large floods (>400,000 cfs) are required to completely rework some aggraded debris fans, Magirl and others (2005) found several examples of debris flows that were effectively removed by modest floods. For example, an 8 to 10 ft (2.4 to 3.0 m) drop at Doris Rapid was nearly completely removed by a 220,000-cfs flood in 1921. Also, a 3.0 ft (0.91 m) riffle at To Hajisho Wash (RM 28.5) in 1923 was completely removed by the 127,000-cfs flood in 1927. While we do not dispute that the amount of reworking increases with the magnitude of floods, effective reworking and redistribution of coarse sediment can occur at a variety of flood discharges and are heavily dependent on particle size of the aggraded debris fan, the elapsed time between debris flow and reworking flood, and the stream power available to transport sediment from a specific debris fan.

Webb and others (1999a) reported that reworking decreases with the time elapsed between the debris flow and the flood event because average releases may interlock particles into an overlapping network, significantly increasing the force necessary to dislodge and carry particles from debris fans. This process that leads to interlocked particles, which is the net result of physical rearrangement, abrasion of particle-particle contact points, and differential dissolution at contact points, is termed "suturing." Suturing is common on debris fans that have not had debris-flow aggradation historically, and we have observed some suturing on recently aggraded debris fans, such as 18 Mile Wash (1987 debris flow) and 127.6 Mile Wash (1989 debris flow), on the distal margin where submergence occurs frequently. The documented occurrence of suturing provides compelling reason to decrease the elapsed time between controlled flood releases, if reworking of aggraded debris fans is a priority.

To understand how rapids have changed over time, water-surface profiles from 1923 and 2000 were compared to detect geomorphic change (Magirl and others, 2005). Magirl and others (2005) compared the longitudinal profile surveyed in 1923 (U.S. Geological Survey, 1924) with a profile constructed from lidar data taken in 2000. Ninety-one tributary junctures along the Colorado River in Grand Canyon between Lees Ferry and Diamond Creek were evaluated for change. These sites represent 39% of all rapids and 67% of named rapids. At these 91 locations, 11 rapids were known to have not changed between 1923 and 2000, 6 rapids exhibited a rise in the elevation at the head of the rapid of 4.6 ft (1.4 m) or more, and the elevation at the head of 2 rapids

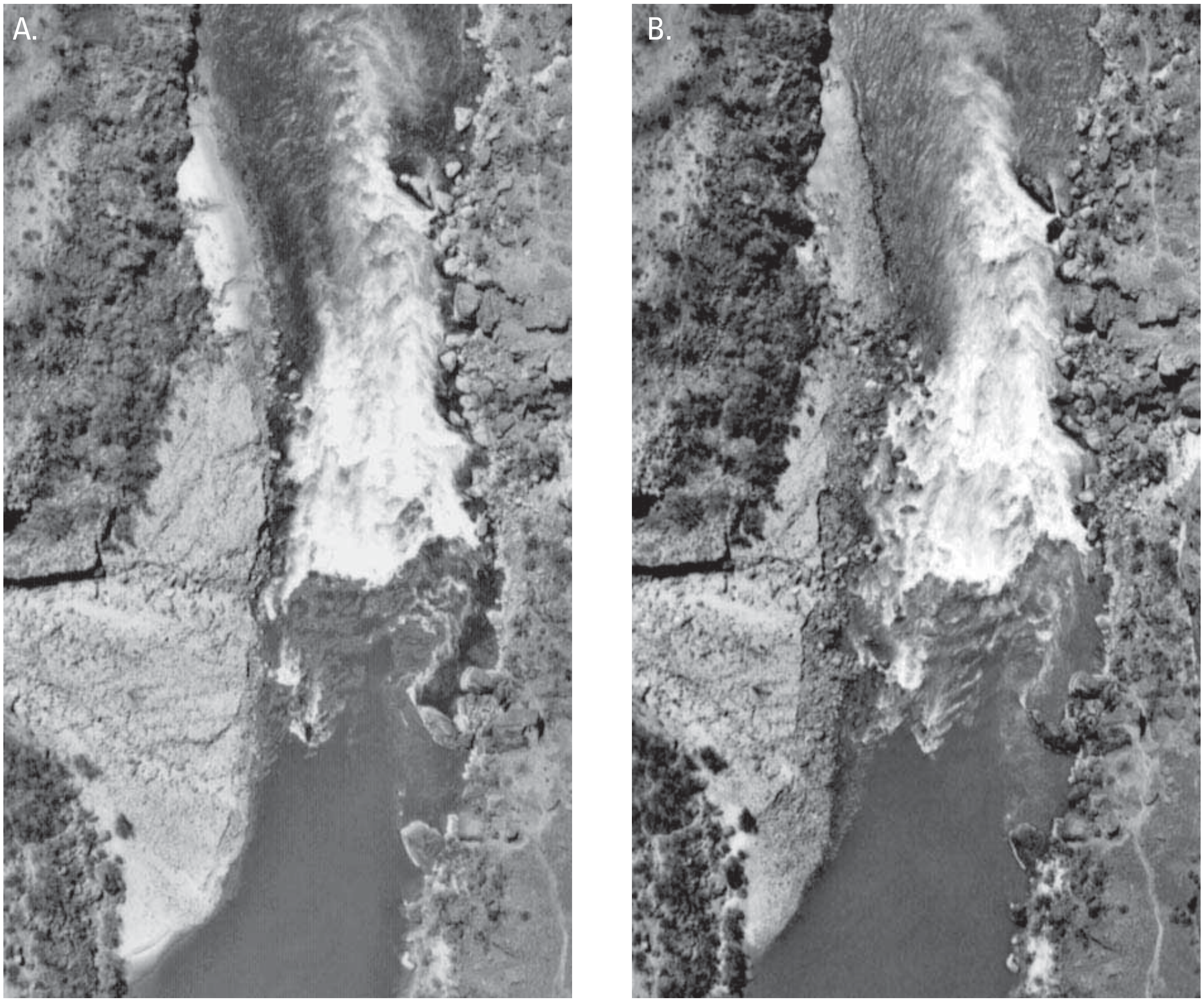

Figure 6. Changes in Lava Falls Rapid (RM 179) during the 1996 beach/habitat-building flow. The river flows from bottom to top in these views. A. (March 24, 1996) The 1995 debris flow from Prospect Canyon (left side of the views) constricted the river by about 60%. This view shows the freshly deposited sediments with no vegetation on river left (left side of the view). B. (April 9, 1996) Reworking by the 1996 beach/habitat-building flow, which had a peak discharge of about 47,500 cfs at Lava Falls Rapid, removed 208,000 ft^3 (5,900 m^3) of the aggraded debris fan, increasing the width of the rapid by an average of 16 ft (5 m) (photographs courtesy of Grand Canyon Monitoring and Research Center, U.S. Geological Survey).

decreased more than 4.6 ft (1.4 m). The net change at 91 rapids is shown in figure 7. More rapids aggraded (18) than degraded (7) for elevation changes greater than or equal to 2.3 ft (0.7 m), which is the threshold of detectable elevation change. Moreover, elevation increases were consistently larger than elevation decreases. Of the 10 debris fans associated with the largest elevation increases, 8 were aggraded by one or more known debris flows since 1923 (table 2 in Magirl and others, 2005). Of the five debris fans associated with the largest elevation decreases, only two had debris flows since 1923 (Magirl and others, 2005). Finally, the average elevation of pools at the heads of rapids was 0.85 ft (0.26 m) higher in 2000 than in 1923.

Comparison of the 1923 and 2000 profiles also reveals the interaction between rapids as a result of debris-flow deposition (fig. 8). The 1966 debris flow at Crystal Rapid (RM 98) caused a rise in river level several miles upstream, which drowned out the tailwaves of Boucher Rapid to create what river runners refer to as "Lake Crystal." The 1951 debris flow at Boucher Rapid had the opposite effect on the tailwaves of Hermit Rapid. The result was one of the larger hydraulic features in Grand Canyon, the notorious fifth wave in

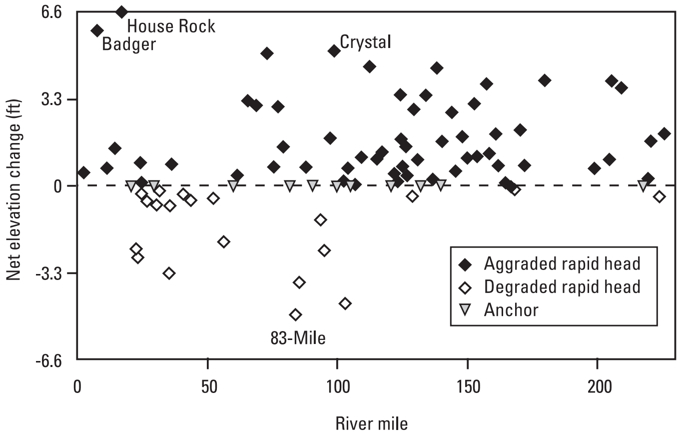

Figure 7. Net elevation change in 91 rapids of the Colorado River in Grand Canyon between 1923 and 2000. The locations of rapids that did not change between 1923 and 2000 and were therefore used to anchor the change in longitudinal profiles are shown as inverted triangles.

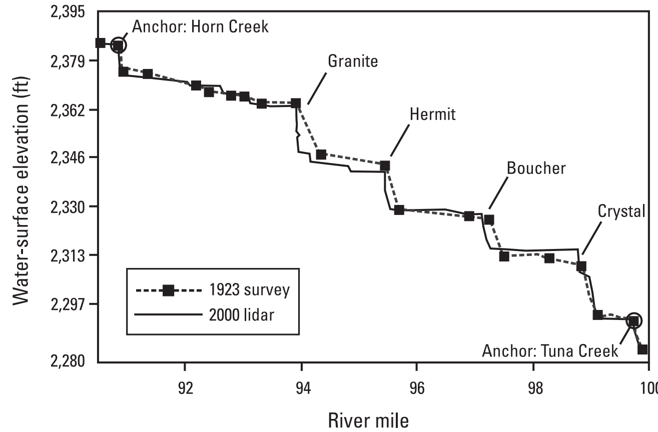

Figure 8. Comparison of 1923 and 2000 water-surface elevation profiles in upper Granite Gorge in Grand Canyon. Despite three debris flows, the head at Granite Rapid has changed little in 77 yr, but its drop has steepened. In contrast, aggradation from the 1966 debris flow at Crystal Rapid is clearly visible in the comparison, and this aggradation affects Boucher Rapid upstream. Likewise, a 1951 debris flow at Boucher Creek has affected Hermit Rapid upstream.

Hermit Rapid, which is a compressional wave associated with the jet of the rapid entering a backwater controlled by an aggraded Boucher Creek debris fan.

Leopold's (1969) analysis of the pool-and-rapid morphology of the Colorado River, which is one of the more widely referenced figures, presents the cumulative vertical drop of the river as a function of distance as measured in 1923 for the first 150 mi (241 km) below Lees Ferry. Leopold concluded that 50% of the total drop occurred in only 9% of the length of the river. In 2000, 66% of the total drop in river occurred in 9% of the length over the 227 mi (365 km) below Lees Ferry. When only the first 150 mi (241 km) of river is considered for direct comparison with Leopold (1969), 71% of the total rapid occurs in 9% of the length (fig. 9), reflecting the greater amount of aggradation in Marble Canyon and eastern Grand Canyon compared to western Grand Canyon.

Impacts of Dam Operations on Aggradation

Operations of Glen Canyon Dam have long been hypothesized to increase aggradation of the riverbed by limiting the reworking of debris fans (Howard and Dolan, 1981; Kieffer, 1985; Webb and others, 1989; Melis and others, 1994; Griffiths and others, 2004). Glen Canyon Dam has reduced peak discharges on the Colorado River, which now has insufficient stream power to transport particles more than 3 ft (0.91 m) in diameter, except during maximum powerplant releases or intentional flood releases and even then only at the largest rapids. Cobbles and boulders carried from debris fans by the regulated Colorado River appear to be redeposited in the pool immediately downstream of the debris fans instead of on the debris bar farther downstream (Pizzuto and others, 1999; Webb and others, 1999b). This altered pattern of redeposition reflects a change in the geomorphic framework of the Colorado River; in the case of Granite Rapid, repeated debris flows and modest reworking from 1984 through 2003 have resulted in a lengthening of the rapid tailwaves through the pool and into the secondary riffle.

Many rapids in the Colorado River system have become larger during the last 30 yr because debris-fan constrictions and individual boulders cannot be totally removed by typical dam releases (Graf, 1979; Howard and Dolan, 1981; Melis and others, 1994; Webb, 1996). Continued deposition of coarse sediment into the river channel by debris flows will likely fill deeper pools above and below rapids while also enhancing the size of eddies; however, with the notable exception of the Crystal Rapid debris flow of 1966, most rapids affected by recent debris-flow aggradation are less hazardous to navigation. Exposed or shallowly submerged rocks are significant navigational obstacles, and debris-fan aggradation tends to narrow the channel, increasing flow depths and either removing or submerging existing rocks. At the same time,

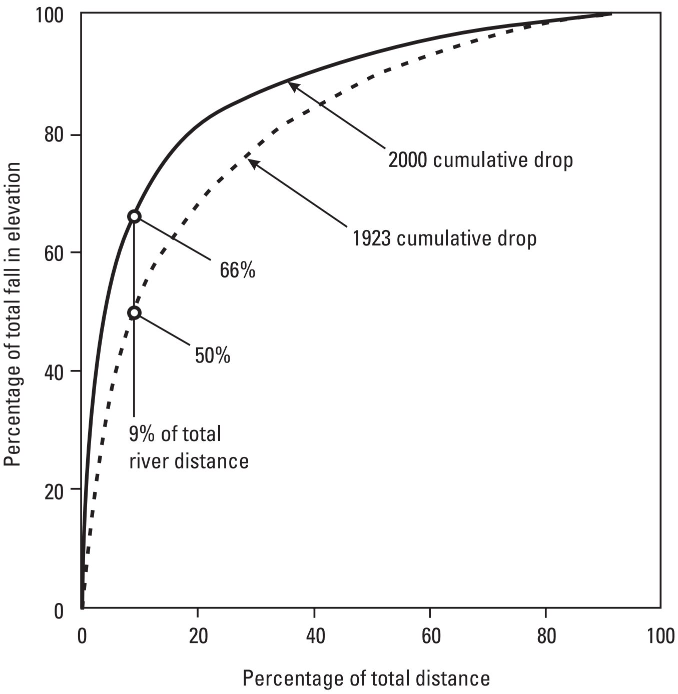

Figure 9. Comparison between the cumulative vertical drop of the river in 1923 (data from Leopold, 1969) and the cumulative vertical drop in 2000 (Magirl and others, 2005).

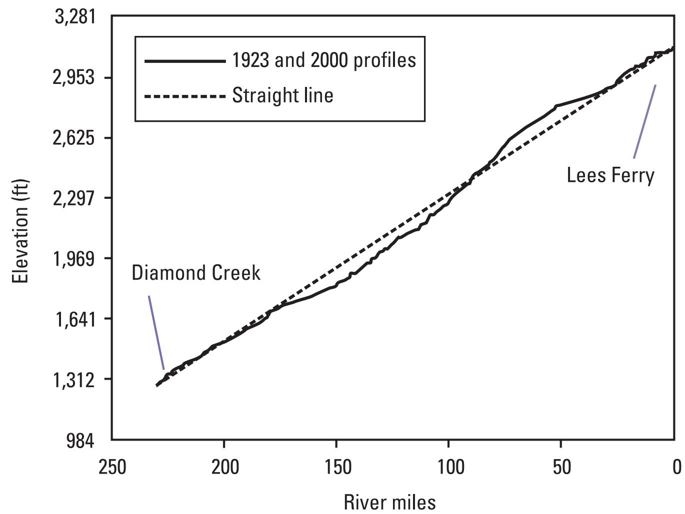

Figure 10. The longitudinal profile of the Colorado River through Marble and Grand Canyons (Lees Ferry to Diamond Creek) as surveyed in 1923 (U.S. Geological Survey, 1924) and as measured by using lidar in 2000 (from Magirl and others, 2005; Hanks and Webb, in press). At this scale, differences in the 1923 and 2000 profiles (see fig. 8) are not apparent. The straight line represents the average river gradient and illustrates profile convexities that appear to be related to debris-flow deposition in the Colorado River.

the drops through these rapids are steeper, and sizes of waves are typically larger; these changes could lead to increased incidence of boat flips.

The Longitudinal Profile of the River

Hanks and Webb (in press) interpreted the longitudinal profile of the Colorado River through Grand Canyon in relation to debris-flow sedimentation at rapids. Rapids represent short-wavelength (about 0.6 mi (1 km)), small-amplitude (less than about 16 ft (5 m)) convexities (areas that round outward from the riverbed) in the longitudinal profile of the river, arising from the shallow gradient in the upstream pool and the steep gradient through the rapid itself. The kinds of changes detected in the comparison of the 1923 and 2000 profiles (Magirl and others, 2005) discussed previously cannot be as easily detected when the longitudinal profile of the Colorado River is displayed for the length of Grand Canyon (fig. 10).

Analysis of the entire longitudinal profile through Grand Canyon reveals two river-profile convexities that are long-wavelength (about 62 mi (about 100 km)), large-amplitude (49 to 98 ft (15 to 30 m)) river-profile convexities (Hanks and Blair, 2003; Hanks and Webb, in press): the eastern canyon convexity between RM 30 and RM 80 and the western canyon convexity between RM 160 and RM 250. Both of these convexities are easily discernable in figures 11 and 12. These large-amplitude convexities have strong spatial correlations with high probabilities of debris-flow occurrence, high densities of debris fans, and the largest debris fans along the river. Convexities of intermediate scale are also identified in the longitudinal profile. River-profile convexities require an active and powerful geologic process to maintain them, in this case the abundant, frequent, and voluminous debris-flow activity in Grand Canyon. Presumably for all of the Holocene and at least some of the late Pleistocene, the Colorado River has been expending its energy transporting sediment within Grand Canyon, integrating short-wavelength convexities into long-wave-

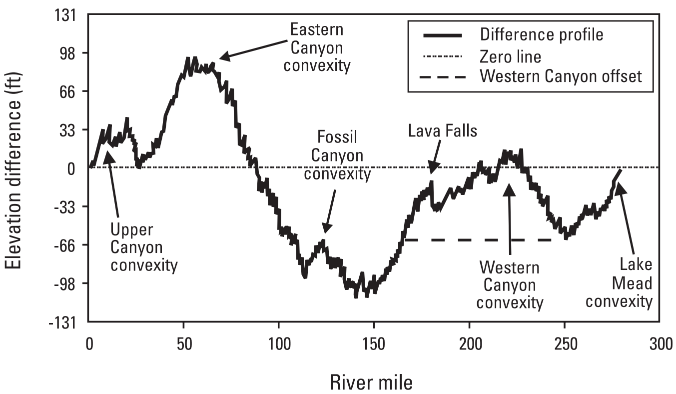

Figure 11. A profile of the difference in elevation (ft) between the longitudinal profile of the Colorado River between Lees Ferry and the Grand Wash Cliffs and its average gradient (both are shown in fig. 10). The Western Canyon offset shows that this convexity likely has a larger magnitude if the true bedrock profile were known. Convexities discussed in this chapter are shown on the profile.

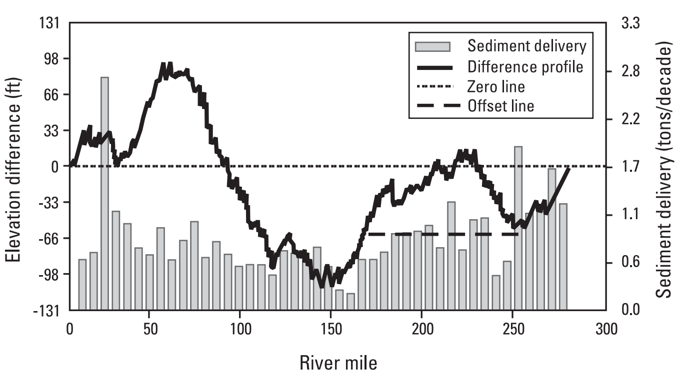

Figure 12. A profile of the difference in elevation (ft) between the Colorado River and an average gradient (fig. 11) compared with a reach-averaged sediment yield for debris flows as calculated by using a stochastic model (Webb and others, 2000).

length convexities. This suggests that little or no bedrock incision has occurred during about the last 11,000 yr.

Detrending of the longitudinal profile (fig. 11) reveals the magnitude of convexities and allows comparison with other features along the river corridor. For example, the largest convexities coincide with reaches that contain 13 of the 14 largest debris fans (Hanks and Webb, in press). In addition, the locations and areas of the 444 Holocene debris fans between Lees Ferry and Diamond Creek (Melis, 1997) coincide with fluctuations in the difference profile (Hanks and Webb, in press).

Hanks and Webb (in press) compared debris-flow probabilities (calculated from fig. 5) averaged over 12.4-mi (20-km) intervals with this difference profile and found that the highest debris-flow probabilities have a strong association with intermediate and long-wavelength convexities. The falling limbs of the Eastern and Western Canyon convexities are both associated with decreasing debris-flow probabilities as they enter the upper and lower Granite Gorge, respectively, reflecting the decrease in the rate of tributary sediment delivery in these reaches. As shown in figure 12, the reach-averaged sediment yield from the debris-flow sediment-yield model is also associated with profile convexities, although the association is less than for the probabilities alone.

Several overall characteristics of the river corridor appear to be associated with the characteristics of long-wavelength convexities. The presence of abundant emergent islands in the river is associated with the tops of the convexities where overall slopes are relatively low. Cultural sites on fine-grained sediment deposits appear to be most common on the tops of large-scale convexities as well. The largest rapids on the river appear to be associated with the falling limbs of convexities (Hanks and Webb, in press). This latter characteristic may result from both the increased reach-scale gradient on the falling limbs of the convexities and a greater spacing between rapids, which minimizes interaction between the drops.

Summary and Management Implications

Debris flows transport poorly sorted sediment onto debris fans in the Colorado River at a frequency that varies through Grand Canyon. Historically, an average of 5.0 debris flows per year has occurred in Grand Canyon. The occurrence of these debris flows does not appear to be related to seasonal precipitation amounts. Modeling debris-flow frequency in Grand Canyon based on the interpretation of 1,365 photographs of the river corridor yielded frequency information in 167 of 740 tributaries (23%). Of the 167 tributaries, 98 (59%) had debris flows during the last 100 yr.

Frequency estimates indicate that 57% of the tributaries had at least one debris flow per century, while about 10% of the tributaries had a frequency of more than two debris flows per century. Estimates of sediment yield to the Colorado River in Grand Canyon by debris flow are as high as 3.3 million tons (3.0 million Mg) of sediment per decade, of which 452,000 tons (410,000 Mg) are boulders larger than 10 inches (>256 mm) in diameter. Distributed evenly throughout the river corridor, these boulders would raise the bed in Grand Canyon by 2.3 ft per thousand years (0.72 m per thousand years). If deposition is limited to existing debris fans at tributary mouths, these boulders would raise the bed by an average of 8.66 ft (2.64 m) per thousand years at each confluence.

By combining the frequency model with relations for debris-flow volume and particle-size distribution, debris-flow sediment yields were calculated for several time periods. On average, debris flows deliver between $0.15 \cdot 10^6$ and $0.33 \cdot 10^6$ tons/yr ($0.14 \cdot 10^6$ and $0.30 \cdot 10^6$ Mg/yr) of sediment to the main channel. Although debris flows deliver only 23,142 to 48,488 tons/yr (21,000 to 44,000 Mg/yr) of boulders to the river, these boulders control the longitudinal profile and geomorphic framework of the river, defining debris fans, rapids, and related sandbars, and are unlikely to be removed by regulated flows. Moreover, the effects of debris flows are shown to affect the river on several length and temporal scales.

Comparison of the two water-surface profiles (one surveyed in 1923 and one in 2000) showed a change in 80 rapids. The average elevation of pools at the heads of rapids was 0.85 ft (0.26 m) higher between 1923 and 2000, indicating net aggradation of the coarse-grained sediment forming the rapids throughout Grand Canyon. Furthermore, comparison of the two water-surface profiles showed enhanced pool-and-rapid structure; while 50% of the total drop of the river occurred in just 9% of the river distance in 1923, that figure increased to 66% by 2000. Reconstruction of water-surface profiles showed that debris-flow deposition can also have large upstream effects, particularly in the cases of reducing gradients between rapids and reducing the fall in the upstream rapid.

Analysis of the entire longitudinal profile through Grand Canyon reveals convexities that reflect sustained debris-flow deposition. Specifically, there are two long-wavelength (about 62 mi (about 100 km)), large-amplitude (49 to 98 ft (15 to 30 m)) river-profile convexities: the eastern canyon convexity between RM 30 and RM 80 and the western canyon convexity between RM 160 and RM 250. These large-amplitude convexities have strong spatial correlations with high probabilities of debris-flow occurrence, high densities of debris fans, and the largest debris fans along the river. These convexities appear to be maintained by debris-flow activity in Grand Canyon, presumably for all of the Holocene. In this period, the Colorado River has been expending its energy transporting sediment within Grand Canyon and integrating short-wavelength convexities into long-wavelength convexities, with little or no bedrock incision.

Coarse-sediment fill in the channel of the Colorado River at any wavelength has its origins in the rapids, which result from the tributary debris flows and fans that feed them. In contrast, the amount of fill in the rapids, either individually or collectively, is a small volume compared to the fill that creates the longer wavelength convexities. Periodic channel maintenance floods are not likely to perform the transport necessary to create the long-wavelength convexities, although reworking of locally aggraded debris fans is clearly feasible. The river-reworking processes by which point-source contributions of debris-flow sediment are aggregated into longer wavelength convexities are as yet unknown and certainly involve a more detailed understanding of the flood dynamics of the predam river. Nevertheless, the close spatial associations of the longer wavelength convexities with the locations and sizes of debris fans and with the frequency of debris flows lead to the conclusion that unusual accumulations of debris fill in the channel are their principal cause, just as they are for the rapids.

In terms of adaptive management and operations of Glen Canyon Dam, reworking of aggraded debris fans has been shown to be feasible. Reworking has been documented during modified low fluctuating flow releases, maximum powerplant releases, and flood releases up to 47,500 cfs. Both reworking and transport capacity increase with increasing discharge, which suggests that flood releases larger than powerplant capacity of about 33,500 cfs are more efficient than smaller events. Because reworking mostly occurred in the rising limb of flood hydrographs, large-magnitude floods designed for debris-fan reworking do not have to have significant duration. As shown in figure 13, a flood designed

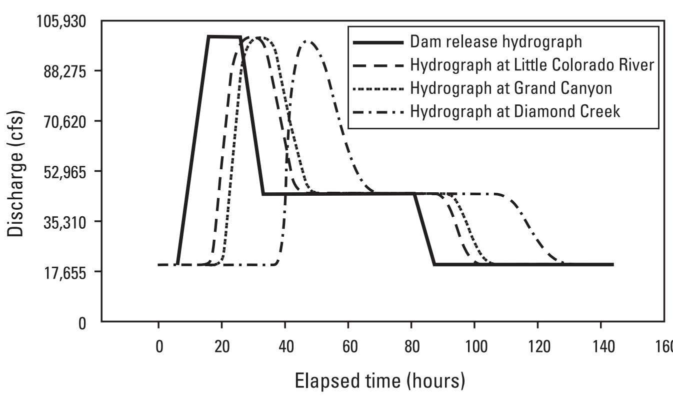

Figure 13. Hypothetical Glen Canyon Dam release and flow hydrographs designed to create a peak discharge of 100,000 cfs for 1 min at Diamond Creek, followed by a beach-building discharge of 45,000 cfs for a duration of 2 d.

to rework debris fans could have a peak discharge of 100,000 cfs for only 1 min at Diamond Creek then drop rapidly to a beach-building discharge for several days. This type of management prescription may be only used every 5 to 10 yr, with smaller intervening releases.

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